AN INVESTIGATION OF THE KINETICS ON STATIC ELECTRICITY BUILD UP AND DECAY ON CARPET

A THESIS

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by

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OF STATIC ELECTRICITY BUILD UP AND [illegible]ECAY [illegible]N CARPET

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SUMMARY

Several samples of carpet from different fibers were studied in this investigation. These included nylon, acrylic, polyester, wool, and polypropylene. The carpet samples included looped pile and cut looped pile. These carpets were tested to determine the rate of static build up, the rate of static decay, and the maximum static charge generated by three different generating materials. The generators were constructed using leather, rubber, and Teflon.

These tests were carried out by using a static measuring instrument, called a *field mill,* and an apparatus of the author's design. The apparatus consisted of a variable speed motor connected to a gear reduction box, which in turn was connected to a 19-inch wheel. On this wheel the carpet samples were mounted. The static-generating material was placed on the carpet, the static charge was set up by revolving the wheel, and was measured by the *field mill.*

Polyester cut looped pile carpet proved to have the highest rate of static build up. Nylon 6,6 cut looped pile carpet had the lowest rate of build up. Nylon 6 looped pile carpet and polypropylene looped pile carpet had the lowest rates of decay. The sample with the highest rate of decay was acrylic looped pile carpet. Nylon 6,6 looped pile carpet set up the greatest static charge while acrylic looped pile carpet set up the least charge. Also, cut looped pile carpets proved to have a slower rate of build up and a faster rate of decay than their looped pile counterparts. In terms of static build up and decay, acrylic carpets proved to be the most desirable carpets while nylon proved to be the least desirable. This is a study providing a method to measure the rate of static build up, the rate of static decay, and the quantity of static charge set up on the carpet samples, and pointing out several possibilities for further study.

CHAPTER I

INTRODUCTION AND HISTORY

Static electricity was first recorded in about 600 B.C. by a Greek scientist, Thales of Milet, who noted that amber, after being rubbed with silk, attracted small particles of various materials. From the Greek word for amber, *elektron,* came the word electricity.[1]

It is known from earlier investigators that there is only one kind of electricity or charge, and the distinction between positive and negative electricity is purely a quantitative one. A negative charge is an excess of electrons and a positive charge is a shortage of electrons.

From accepted atomic theory one may say that atoms are made up of neutral as well as positively and negatively charged particles. The neutral particles are called neutrons, the positive particles protons, and the negative particles electrons. Electrons surround the nucleus which is made up of protons and neutrons. The normal atom has the same number of electrons and protons, thus having a neutral over-all charge. In a conductor some of these electrons are sufficiently mobile to move freely, and in doing so produce electric currents. However, charges on nonconductors or insulators are immobile. Under certain conditions an atom may lose or acquire one or more electrons and is then called a positively or negatively charged ion, respectively.[2]

An example of the presence of static electricity or of an unbalanced charge of two bodies is the spark produced when a person walking on a nylon carpet touches a metal object. However, perhaps the most common and certainly the most dramatic example of the presence of static electricity is lightning. Here the accumulated small charges on water droplets give a cloud a tremendous potential. The discharge of lightning may be between two clouds, which have accumulated opposite charges , or from a cloud to earth. A third example of static electricity is the attraction of very light particles by a charged body, such as Thales of Milet observed. This attraction accounts for the dirt which clings to clothing, furniture covers, and carpets that have been previously rubbed in some manner.

Coulomb[3] (1736-1806) and other early experimenters did much to clarify the phenomenum of static. It is known that like charges repel and unlike charges attract each other. Coulomb established a quantitative law about these forces. It states that the electrostatic attraction between two charged bodies is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. Helmholtz[4] (1821-1894) introduced the contact potential theory of electrification of insulators. Moreover, P. E. Shaw[5] showed the important influence of chemical and physical conditions of surfaces involved in static generation.

In the past two decades, research on static gained in importance due to the problems arising in the textile and paper industries. These problems arose from the introduction of excellent insulating materials as well as higher processing speeds.

CHAPTER II

GENERATION AND NATURE OF STATIC

Theories of Generation

The basic concept of static electrification, usually attributed to Helmholtz, assumes that when two materials come into contact a charge is transferred from one to the other. This transfer forms an *electrical double layer* consisting of two layers, each with an opposite charge, on or near the surface separated by a few angstrom units.[6] See Figure 1. These two bodies with the small separation between them act as a capacitor. Therefore, when the two bodies are separated, a large potential is produced, provided the surfaces retain their charge. This is due to the decrease in capacitance.

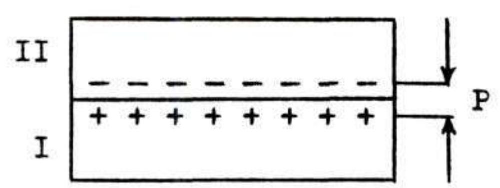


Figure 1. Electrical Double Layer.[7]

$$C = \frac{AO}{4\ P} \tag{1}$$

where C = capacity

A = dielectric constant

O = area of surface contact

P = distance between charges

As P increases, the capacity decreases.

$$V = \frac{E}{C} \quad \text{or} \quad E = CV \tag{2}$$

where V = potential

C = capacity

E = total surface charge of one body

As the capacity decreases the potential increases. Therefore, the greater the separation between surfaces the larger the potential of the surfaces.

Static is increased by rubbing because the area of the double layer is increased and energy is added to the system.

Solids can be classified into conductors, insulators, and semi-conductors. A conductor has a high conductivity which decreases with rise in temperature, and also with increase of impurities. An insulator has a very low conductivity. The conductivity of a semi-conductor increases with temperature and with added impurity, but the conductivity decreases at low temperature and high purity.

Early theories of conductivity of metals assumed that valence electrons were free to move to all parts of the metal. This theory met with some success, but it was unable to explain materials which were poor conductors or non-conductors. With the introduction of the wave mechanical concept of the electron, a new theory came into being. It held that the electrons existed in a closely spaced spectrum of energy levels. This spectrum is discontinuous, consisting of bands of allowed states separated by bands of *forbidden* states.[8]

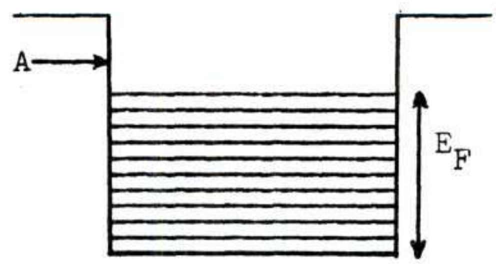
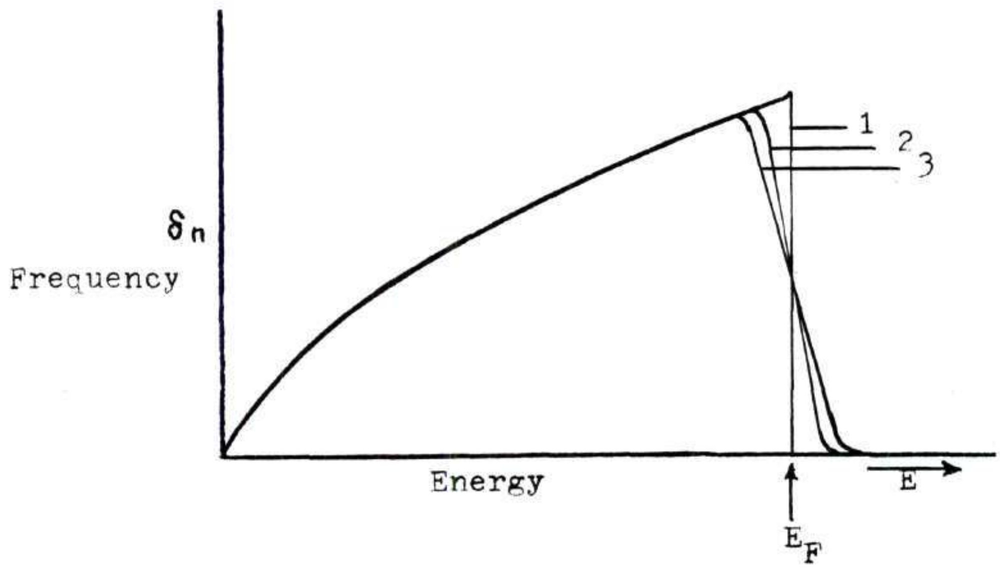


Figure 2. Energy Levels of a Metal.

Figure 2 represents the continuous spectrum of a metal filled up to energy level A and empty above that.

Pauli's Exclusion Principle says that no two electrons in an atom can exist in the same quantum state. Therefore, only two electrons with anti-parallel spin may occupy each state, so that at absolute zero all levels up to energy E_F are filled. The highest occupied level at absolute zero is the Fermi level and E_F is the Fermi energy. At higher temperatures some electrons near the Fermi level may acquire enough energy and move to a higher level. The distribution of electrons in the levels at any temperature is given by the Fermi-Dirac distribution.[9]



1 = absolute zero
2 = room temperature
3 = elevated temperature

Figure 3. Fermi-Dirac Distribution.

It will be observed that even at higher temperatures very few electrons have energies in excess of E_F.

The energy necessary to raise an electron to a higher level can be acquired by acceleration in an electric field, but such motion is only possible when there is a vacancy in the level immediately above the electron. Thus electrons near the Fermi levels are the only ones available to advance a level and take part in conduction.

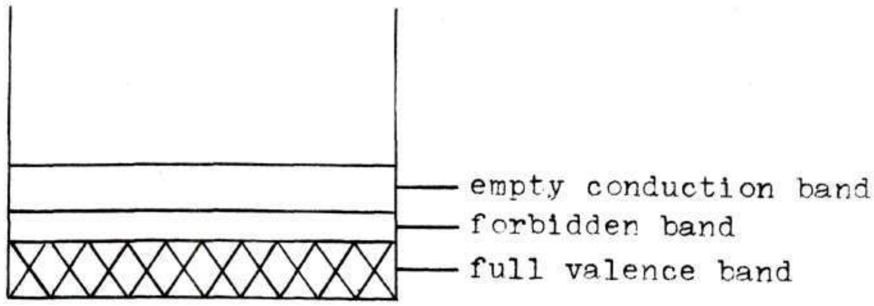


Figure 4. Energy Levels of an Insulator.

In certain materials the energy spectrum is discontinuous. The energy levels are divided into bands separated by a forbidden band. The lower or valence band is full and the upper conduction band is empty. Since the valence band is full and an electron at the top of the valence band has no higher energy level available, no acceleration in an electric field is possible. The solid is therefore an insulator.

The width of the forbidden band in most non-metallic solids is of the order of five to ten electron volts, but in a few substances, such as silicon and germanium the width is of the order of one electron volt. In such materials temperatures a little above room temperature are great enough to give electrons sufficient energy to rise to the conduction band, and produce some conductivity. Such a material is referred to as an intrinsic semi-conductor. In theory, an insulator should become a conductor at high temperatures, but usually melting occurs first.[10]

The energy bands of a semi-conductor are similar to those of an insulator, but include isolated levels within the forbidden band.

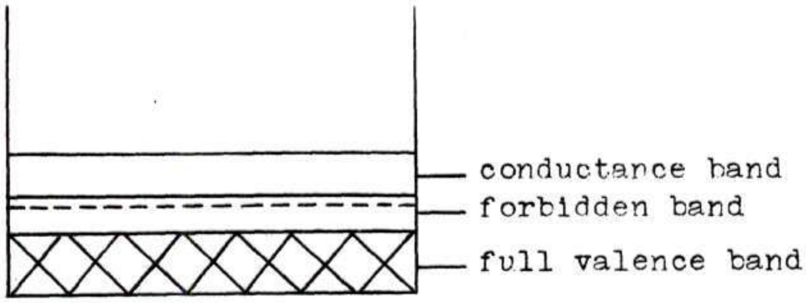


Figure 5. Excess or n-type Insulator.

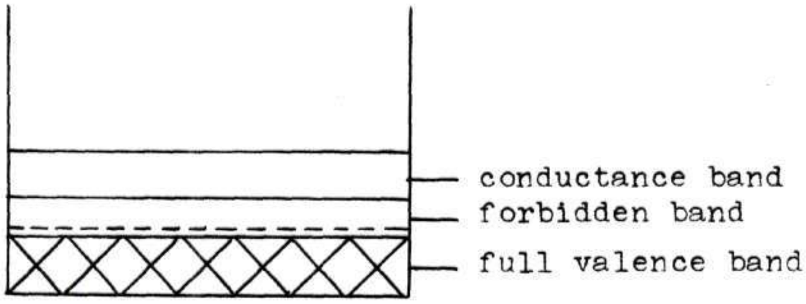


Figure 6. Defect or p-type Insulator.

There are two main types of semi-conductors in addition to the intrinsic type. In the excess, or n-type, the extra levels are not far below the conductance band and have electrons in them. In defect, or p-type, the extra levels are just above the valence level and are usually empty. In an n-type semi-conductor the carriers of the charge are electrons, but in the p-type the carriers are the *holes* left in the valence band after the electrons have gone into their new p-levels. These holes move under the influence of an applied field as though they have positive charges. As the temperature increases the semi-conductors will become more like conductors.[11]

Substances in Contact

When two materials which have different Fermi energies are placed in contact, electrons will flow from the one with the highest Fermi energy to the one with the lowest Fermi energy, so as to equalize the Fermi levels. With the metal-metal contacts, the time for the electron transfer is very short, and in some cases can be considered instantaneous. In the case where one or both of the contacting materials are insulators, the transfer time may be very long at room temperature. For good insulators it may take years to reach equilibrium.

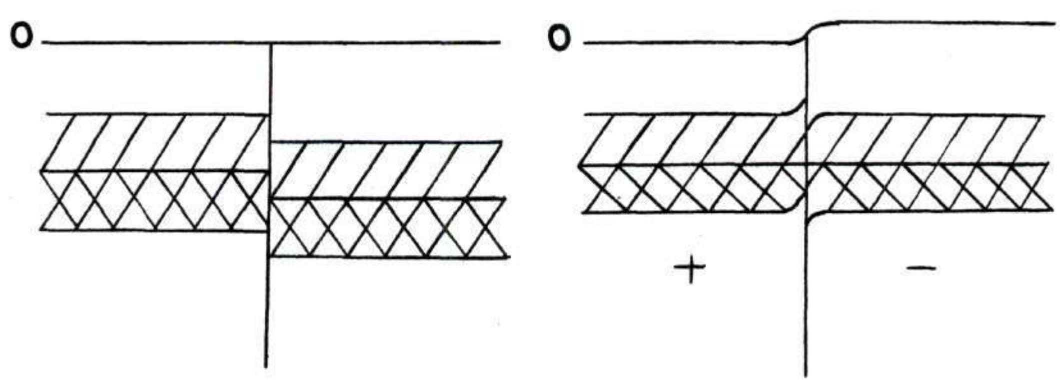


Figure 7. Metal-Metal Contact, Energy Levels at the Surface Before and After Contact.

Figure 7 represents the contact between two metals. Electrons in the partially-filled band on the left flow over to the partially-filled band on the right. There are many electrons available and many vacant levels for them to fill. A charge of 10^4 esu/cm^2 is lost by the left-hand material from a small region, approximately one angstrom unit thick, and an equal charge is gained by the right-hand metal within a small region.

Figure 8 represents the contact between two insulators. Figure 8(a) represents the separate materials when the Fermi levels do not overlap an empty band in the other. Electrons can pass from the left-hand insulator to the right-hand one only by thermal agitation from a filled band into an empty band at a higher energy. Hence a small charge of 10^{-1} esu/cm^2 is lost by the left-hand insulator to the right-hand insulator.

Figure 8(b) represents the contact between insulators when a filled band in one material overlaps an empty band in the other. Electrons can now spill from the filled band of the left-hand material into the empty band of the right-hand material. Hence a large charge of 10^4 esu/cm^2 is lost by the left-hand insulator from a small region, about ten angstroms thick, and an equal and opposite charge is gained by the right-hand insulator.

Figure 9(a) represents the contact between metal and insulator. When in isolation the Fermi level in the metal lies below the Fermi level in the insulators, and when the top of a filled band of the insulator lies above the Fermi level in the metal, then electrons can spill from the filled band in the insulator to the half-filled band

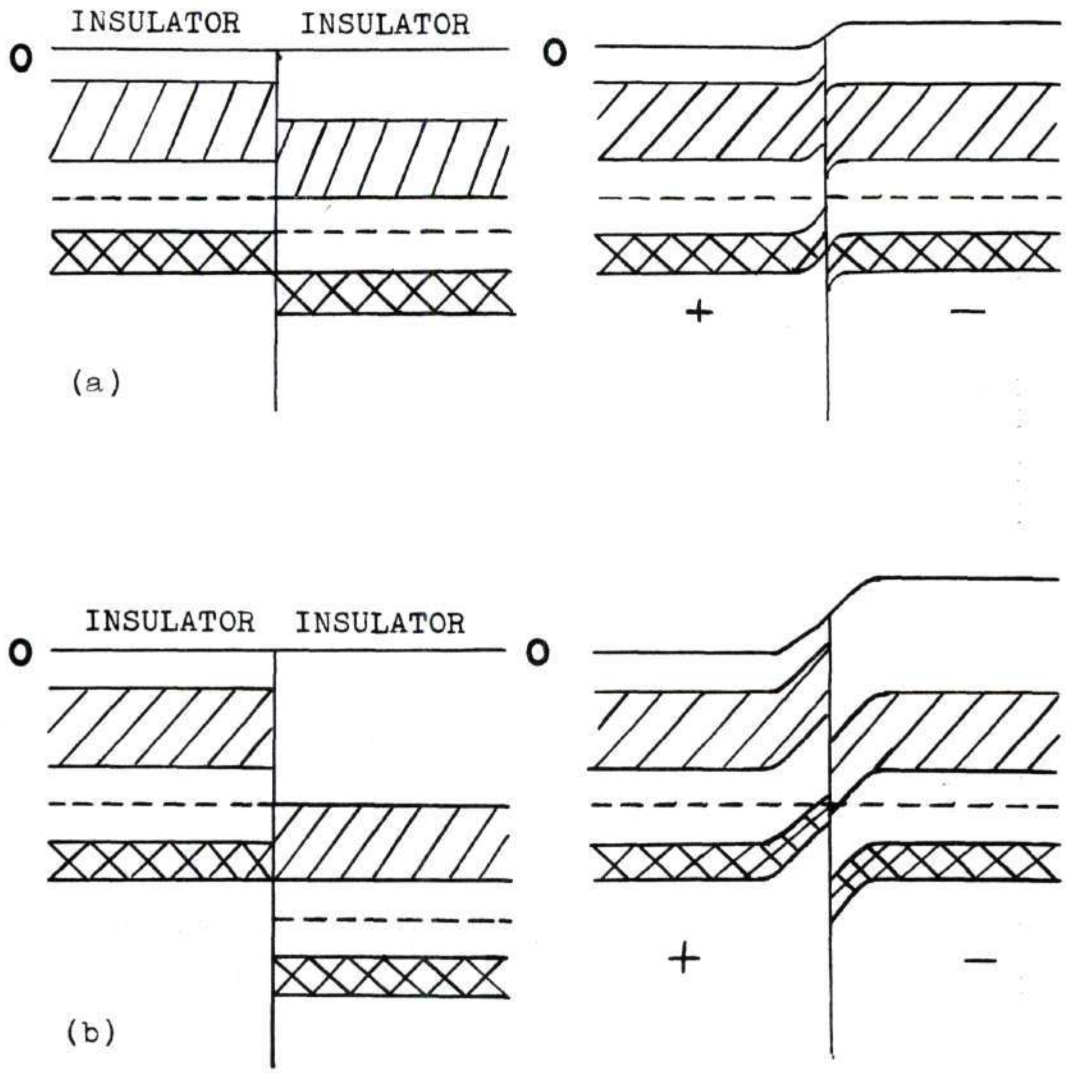


Figure 8. Insulator-Insulator Contact, Energy Levels at the Surface Before and After Contact.

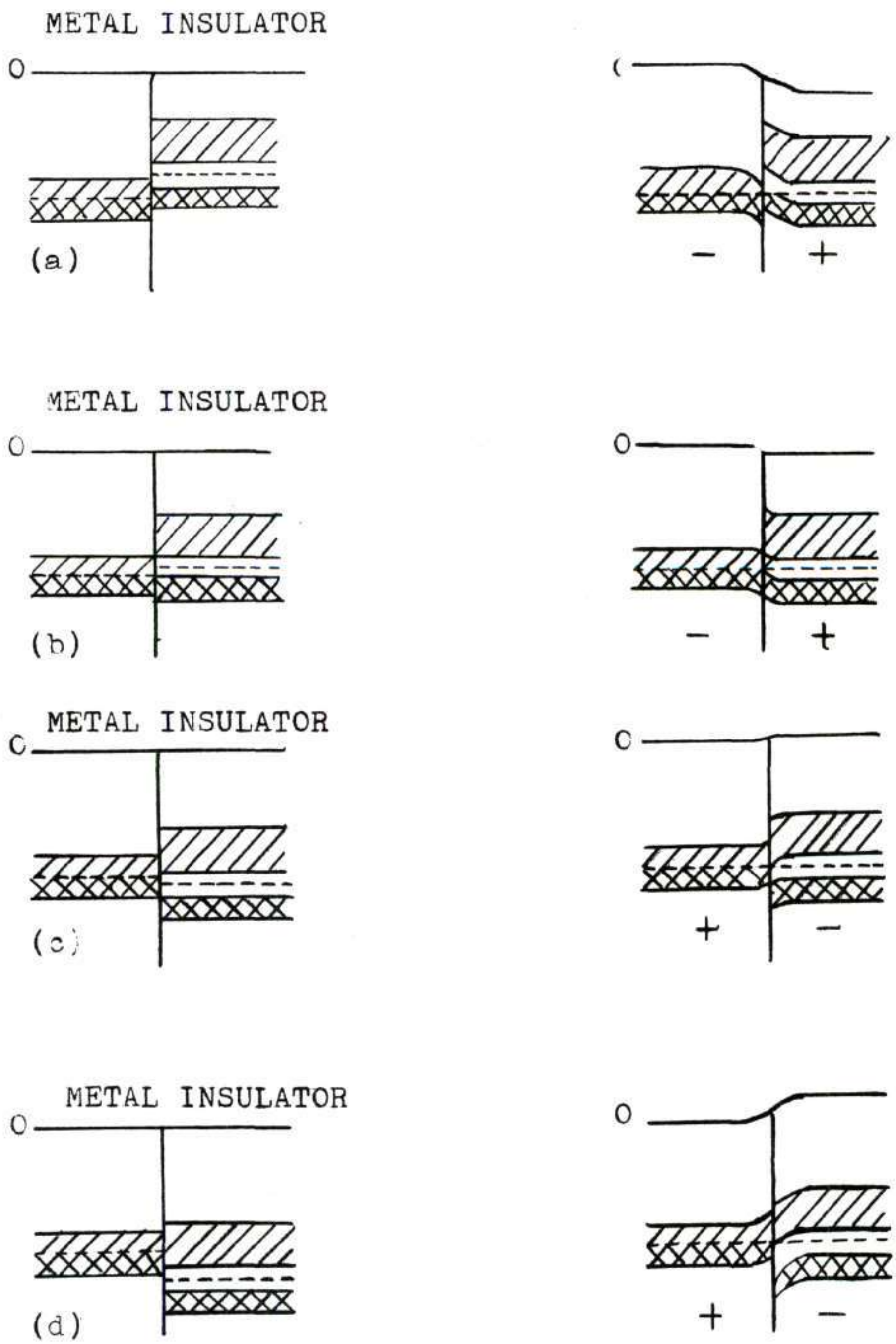


Figure 9. Metal-Insulator Contact, Energy Levels at the Surface Before and After Contact.

in the metal. Hence, much charge is lost by the insulator and much gained by the metal.

Figure 9(b) represents the case when the Fermi level in the metal lies below the Fermi level of the insulator, and when the top of the filled band of the insulator lies below the Fermi level in the metal. Then the electrons can escape from the insulator only by thermal agitation from the filled band in the insulator to the partially-filled band in the metal. A small charge is lost by the insulator and an equal charge gained by the metal.

Figure 9(c) represents the case when the Fermi level in the metal lies above the Fermi level in the insulator, and when the bottom of the empty band of the insulator lies above the Fermi level in the metal. Then electrons can escape from the metal only by thermal agitation from the half-filled band in the metal to the empty band in the insulator. A small charge is lost by the metal and an equal charge gained by the insulator.

Figure 9(d) represents the case when the Fermi level in the metal lies above the Fermi level in the insulator, and when the Fermi level in the metal lies above the bottom of an empty band in the insulator. Then the electrons can spill from the partially-filled band in the metal into the empty band in the insulator. A large charge is lost by the metal and an equal charge gained by the insulator.

After separation the transferred charge is localized at the place of contact in the insulators but not, of course, in the metals.[12]

The charge transferred on a surface will, upon separation, be reduced by tunneling through the gap formed by the separating surfaces.

W. R. Harper[13] found while studying metals that a fractional charge remaining is nearly independent of the speed of separation, and it may be concluded that this fraction is of the order of one-half. The fraction will be reduced in the insulator-conductor case, because of the inability of the charge remaining on the insulator to redistribute itself on the surface. Some estimates in the insulator-insulator cases suggest that the fraction will not decrease below one-tenth.

Rubbing two surfaces together has two general recognized effects. The main result gained from rubbing is that it increases the area of the double layer between the two surfaces. The second result is that the friction created raises the surface temperature giving electrons greater energy. Without such rubbing the transfer of charges will occur only at a relatively few places since, by molecular standards, the surfaces of most solids are rough.[14]

Another important variable in determining the true surface of contact is the normal force applied to the surfaces. The charge increases with increasing normal force.

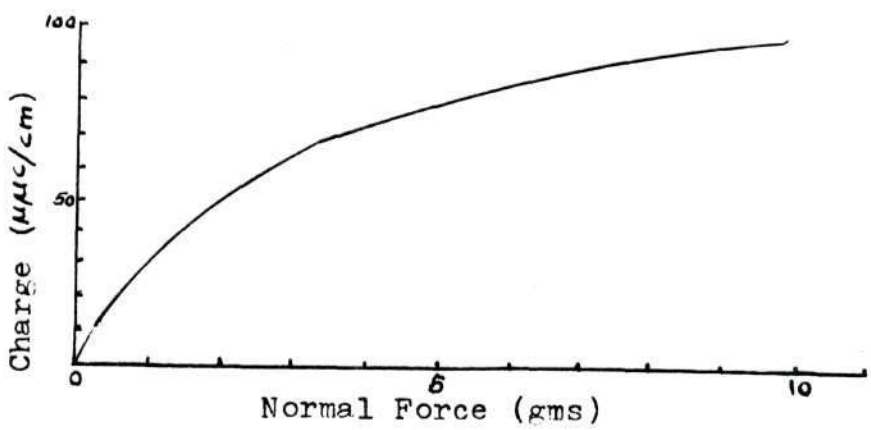


Figure 10. Effect of Normal Forces on Static.[15]

The velocity of the rubbing motion also increases the charge through two main effects: (1) it decreases the time available for charge flow through the gap on separation, and for time to flow away from the point of contact; and (2) it increases the temperature of the surfaces.

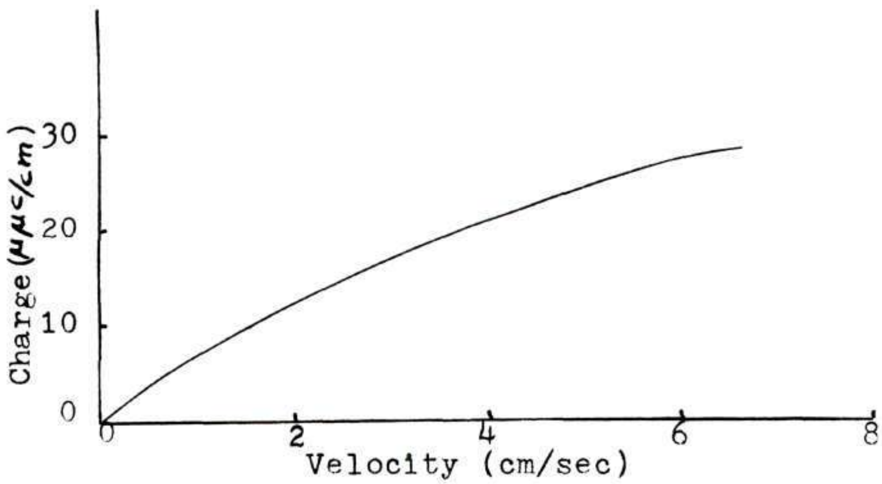


Figure 11. Effect of Velocity on Static.[16]

Static Decay

As was previously shown, static will be generated in any case when two surfaces are brought in contact or rubbed together, regardless of the material. As soon as the surfaces are separated, the charges begin to leak away to the surroundings. If the materials are good conductors, the charges may last from a fraction of a second to a few seconds. On good insulators the charges may remain for minutes or hours, since the charges are not mobile. Dissipation of charges on good insulators may take many different forms. The charge may be reduced by a conducting fluid on the surface, such as moisture, or an ionized gas may remove it from the surface. Other methods such as radiation or a nearby electric field may remove the charge on the material.

Electrostatic Series

Gayler, et al.,[17] defined an *electrostatic series* as a "grouping of materials arranged according to their electrostatic susceptibility." An electrostatic series, see Table 1, is arranged in a vertical list so that any material rubbed against another lower on the list will acquire a positive charge. Conversely, if an item is rubbed against a material higher on the list, it will acquire a negative charge.

It will be noted that there is variation within each of the individual series. This is attributed to variations in testing conditions, purity of the materials, and methods used in measuring static.

The first series was established by J. C. Wilcke in 1757, but the most famous series is the one arranged by Coehn.[22] This series led to "Coehn's First Rule," published in 1898, which states that when two substances are separated, the one having the higher dielectric constant is positively charged. Richards[23] in 1920 found evidence of Coehn's rule with solids. Today it is found that Coehn's rule holds for some solids, but does not always hold in general.

Richards' Equation: (3)

$$\frac{Q}{A} = K(D_1 - D_2)$$

Table 1. Electrostatic Series

Lehmicke[18]	Hersh and Montgomery[19]	Frotscher[20]	Frotscher	Ballou[21]
	33% R. H.	35% R. H.	65% R. H.	15% R. H.
+	+	+	+	+
Glass	Wool	Glass	Glass	Wool
Human Hair	Nylon	Wool	Wool	Nylon
Nylon Yarn	Viscose	Steel	Viscose	Silk
Nylon Polymer	Cotton	Viscose	Cotton	Viscose Rayon
Wool	Silk	Cotton	Acetate	Cordura Rayon
Silk	Acetate	Acetate	Polyacrylo-	Cotton
Viscose Rayon	Lucite	Polyester	nitrile	Fiberglass
Cotton	Polyvinyl-	Polyacrylo-	(Steel)	Spun Ramie
Paper	Alcohol	nitrile	Polyester	Cellulose
Ramie	Dacron	Polyethylene	Polyethylene	Acetate
Steel	Orlon			Dacron Yarn
Hard Rubber	Polyvinyl-	-	-	Orlon Yarn
Acetate Rayon	chloride			Polyethylene
Synthetic Rubber	Dynel			Saran
Orlon	Velon			
Saran	Polyethylene			-
Polyethylene	Teflon			
-	-			

D_1 and D_2 = dielectric constants of contacting material

Q = quantity of charge

A = area of contact

K = constant = 4.4 when Q is in es units

This equation was obeyed within 14 per cent for solids whereas Coehn's agreement among liquids was much closer.

Triboelectricity is electricity generated by friction. Bollou[24] noted one feature of a triboelectric series, namely, the chemical grouping of the materials. Generally, materials containing amide groups such as nylon, wool, and silk are found at the positive end. Polymers which contain several hydroxy groups are found in the center, and hydrocarbons and halogenated hydrocarbons are found at the negative end.

High moisture regain causes a great increase in the dielectric constant, because water has a high dielectric constant of 81. According to Coehn's rule, this would shift materials of a high moisture regain toward the positive end as seen in the table.

There is a correlation of the triboelectric series with the sequence of materials when arranged according to their light fastness. Static susceptibility is related to the tendency of materials to lose electrons upon absorbing light quanta. Therefore, materials with the least light fastness are found at the positive end of the series and those with good light fastness at the negative end.

Dielectric Constant

The dielectric constant, or permittivity, of a material is the ratio of the attracting force between two charged bodies in a vacuum to the force which is found when the bodies are separated by this material.

The dielectric behavior of a material corresponds to the degree of polarization within the material. The polarization is due to the alignment of permanent dipoles or to formation of induced dipoles. A dipole is any oriented configuration whose ends are oppositely charged. For example, water is a permanent dipole. The positive hydrogen ions are situated on one end and the negative oxygen ions on the other. When an external electrical field is applied, polarization takes place through an alignment of these dipoles. The negative ends turn toward the positive side of the field and the positive ends turn toward the negative side of the field. The external field is then superimposed by many small dipole fields oriented in the opposite direction which therefore results in a reduction of the field strength.[25]

The easier the alignment of dipoles in a material, the greater will be the counterfield formed by the dipoles, and the greater will be the dielectric constant. The correlation between dielectric constants and the electrostatic series can be easily seen from this. The easier it is to induce polarization in a material, the easier it should be for an electron to leave its surface. Therefore, the surface with the highest dielectric constant would be positive as is the case with many materials.

A major factor controlling the dielectric constant is the amount of moisture present in the material. For most fibers, the dielectric constant increases rapidly over the whole range of increase of moisture content. For example, the dielectric constant of cotton is 3.2 at zero per cent relative humidity and 18.0 at 65 per cent relative humidity. This is due to the high dielectric constant of water, which is 81. This leads to the assumption that water frees other units in the structure of the fiber and enables them to polarize. Wool experiences increases of this kind only when high moisture content is achieved. This is explained by the fact that the water first absorbed by wool is firmly bound to the hydrophilic group in the side chains of the keratin molecule.[26]

CHAPTER III

INSTRUMENTATION AND PROCEDURE

One of the oldest devices used to measure static electricity is the electrostatic voltmeter, commonly called electroscope. This instrument is still used extensively by physicists. Within the electroscope two thin gold foils hang side by side, and are insulated from a grounded metal housing. These foils are fastened to a metal probe projecting through the top of the housing. When the probe is connected to a voltage source both foils will be charged with the same sign and will repel each other. The angle of deflection is a direct measure of the charge.

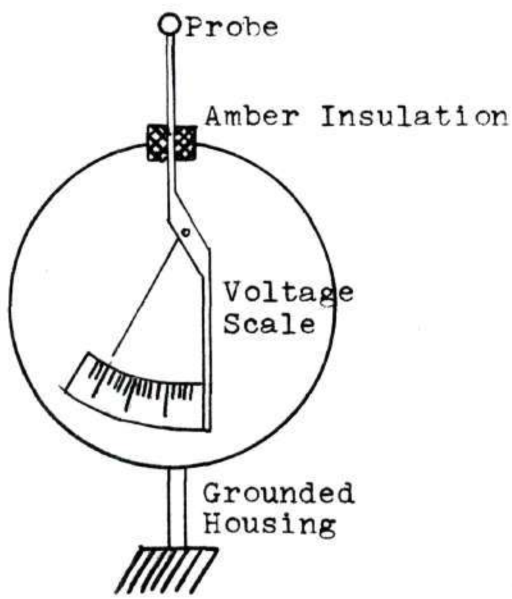


Figure 12. Electroscope.

If a charged conductor is connected to an electroscope, the charge will be evenly distributed over the connected metal parts. However, there is no known satisfactory way to transfer a charge from an insulator to an electroscope. On an insulator, charges are confined to one position and cannot migrate. Charges from the vicinity of the area of contact can be measured but not the whole charge. If the insulator is moved along the probe, new charges will be generated by this action which may add or subtract from the charge being measured.

The instrument used in these measurements is a static voltmeter called a *field mill.* Schwenkhagen[27] first described the principle of the *Field Mill* in 1943. Many modifications have been made since then. With this device the electrostatic field formed between the charged material and the stationary sensing electrode, is chopped by a grounded rotating head.

In Figure 13 the electrode is exposed to the field. When the shield rotates to a position between the electrode and the charged material, the electrode is shielded from the field. By this method an alternating potential is induced on the electrode. Because this potential is changing according to the frequency of the chopper, an AC-current is set up. This AC-signal has an amplitude which is proportional to the field strength. This signal can then be amplified and read off an AC-meter.

Gayler, et al.,[29] state that "'the Field Mill' principle is regarded as the only really accurate and reliable system to measure static by induction . . ." and that the *Field Mill* is "the most convenient, accurate and trouble free instrument available for measuring

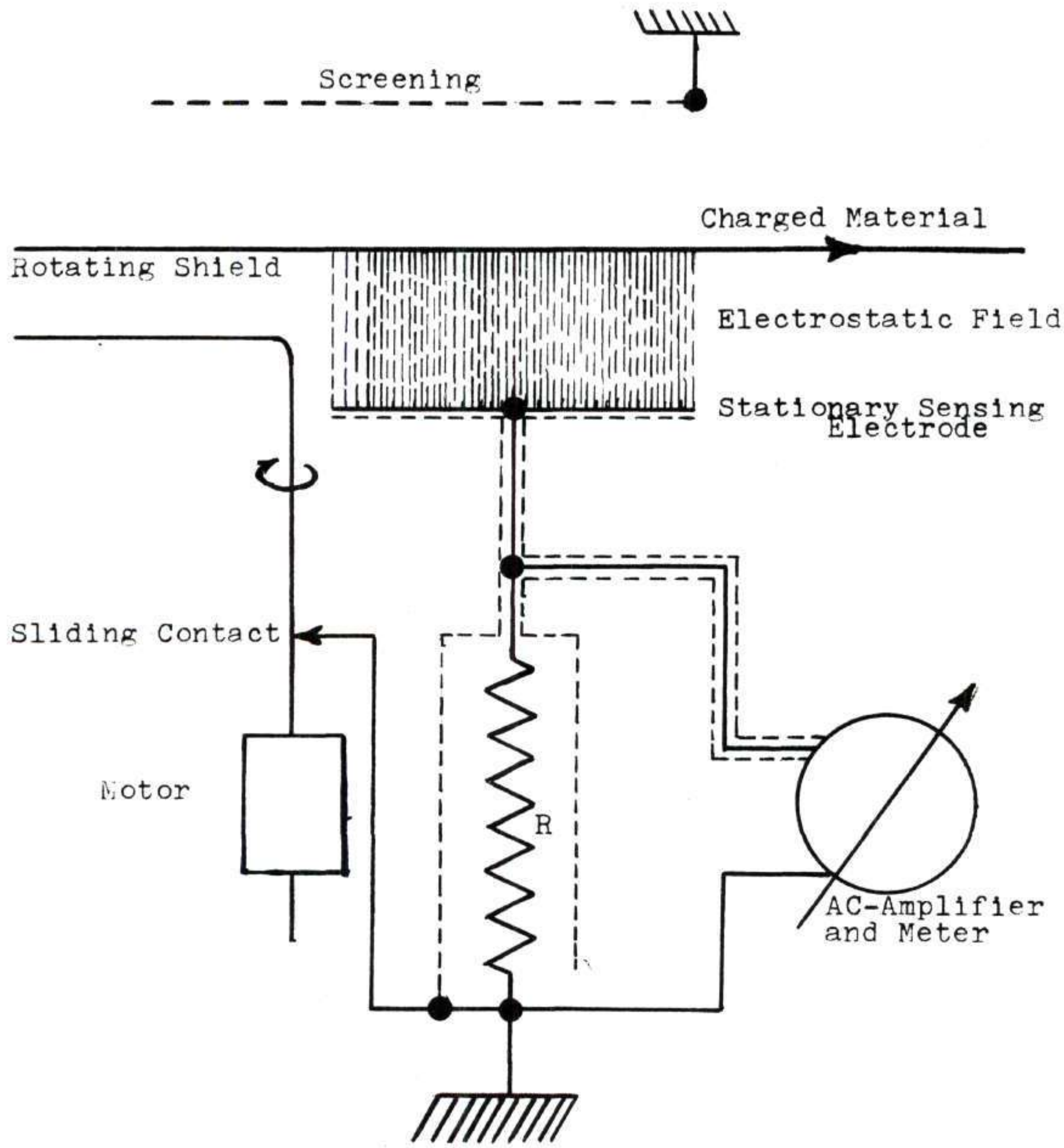


Figure 13. Field Mill[28]

static inside and outside the laboratory even when operated by unskilled personnel."

In this work the field mill was used to measure static charge set up on carpets attached to a rotating wheel of variable revolutions per minute. A variable speed motor capable of producing 75 to 442 rpm is connected to a gear reduction box having a 15 to 1 ratio. This gear box is then connected by means of sprockets to the wheel shaft, with a two-to-one reduction sprocket system being used. The speeds obtainable from this system vary from 2-1/2 to 14-1/2 revolutions per minute. See Figure 14. The sample wheel is covered with cork to prevent the carpet sample from being grounded. The samples are attached to the wheel by use of C-clamps, which are also insulated by cork.

Data for static build up are taken every 15 seconds, while data for static decay, being a much slower process, are taken every minute for the first 5 minutes and every 5 minutes thereafter for an hour.

The different samples of carpet studied were constructed from fibers of nylon, polyester, acrylic, wool, and polypropylene. These carpets had varying types of pile, looped and cut looped. The three types of static generators used were rubber, Teflon, and leather. Each carpet sample was tested using each of the static generating materials.

There were several distances and measurements kept constant throughout the entire experiment. These constants were the distance between the sensing head and the carpet, the distance between the sensing head and the static generating material, and the force on the static generating material. Throughout the entire investigation the

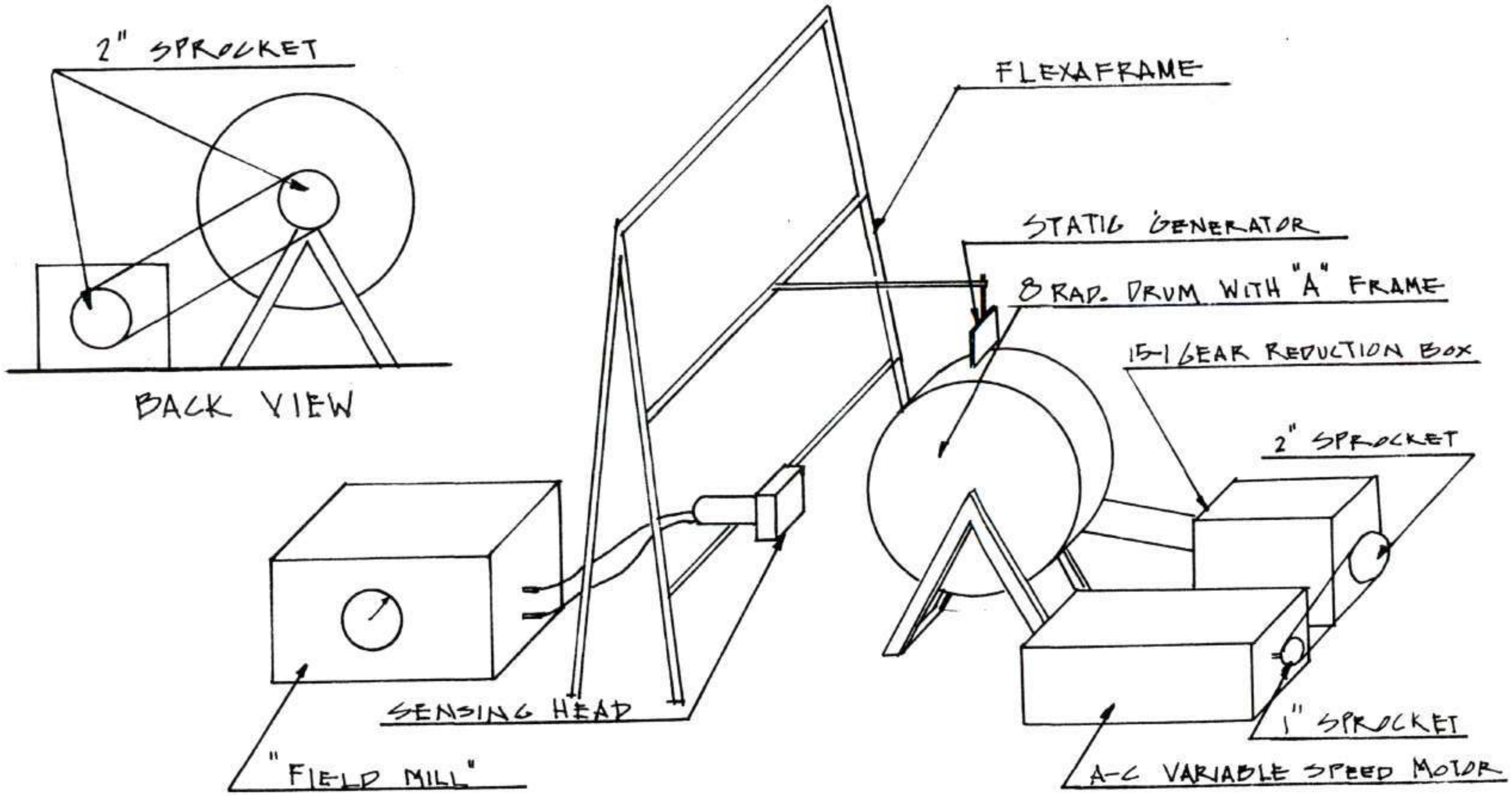


Figure 14. Diagram of Instrument Used to Measure Static Build Up and Static Decay on Carpets.

same samples of Teflon, rubber, and leather were used to prevent any irregularities in these materials from becoming a factor in the experiments. This was done to insure that the results were comparative.

Humidity and temperature were regulated by an air conditioning system and a silica gel dehumidifying unit. The temperature was held at 72° Fahrenheit and the relative humidity at 38 per cent throughout these experiments.

CHAPTER IV

RATE OF STATIC BUILD UP AND DECAY

Build Up of Static

The carpet samples chosen were of medium weight, 23 to 25 ounces per square yard, and were of medium pile height.

Rubber and leather were chosen as static generating materials, since shoe soles and heels are usually made from these materials. Teflon was chosen also since it is at or near the bottom of the electrostatic series. These three choices also gave a range of materials from the electrostatic series. It can be noted from Figures 15, 16, and 17 that leather gave the highest number of negatively charged readings and Teflon gave the lowest. Leather is the highest of the three in the electrostatic series and Teflon is the lowest, with rubber in between leather and Teflon.

In Figures 15, 16, and 17 all the carpets which have static charges above 30 kv/m are either nylon or polyester; all the others are below 30 kv/m and 50 per cent of the samples lie below 15 kv/m. In the case of rubber and Teflon, 60 per cent of the samples lie below 15 kv/m and only 25 per cent lie above 30 kv/m. Those samples which do lie above 30 kv/m, in the case of rubber and Teflon, are all nylon samples. In the instance of leather the static charges are widely distributed; 30 per cent of the samples lie below 15 kv/m and 30 per cent of the samples lie above 45 kv/m. Of those which have

Table 2. Index of Carpet Samples

Experiment Number	Carpet Fiber	Carpet Type	Static Generator
1	Nylon 6	Looped	Teflon
2	Nylon 6	Looped	Rubber
3	Nylon 6	Looped	Leather
4	Polypropylene	Looped	Leather
5	Polypropylene	Looped	Rubber
6	Polypropylene	Looped	Teflon
7	Acrylic	Looped	Teflon
8	Acrylic	Looped	Rubber
9	Acrylic	Looped	Leather
10	Nylon 6,6	Cut	Leather
11	Nylon 6,6	Cut	Rubber
12	Nylon 6,6	Cut	Teflon
13	Acrylic	Cut	Teflon
14	Acrylic	Cut	Rubber
15	Acrylic	Cut	Leather
16	Polyester	Cut	Leather
17	Polyester	Cut	Rubber
18	Polyester	Cut	Teflon
19	Wool	Looped	Rubber
20	Wool	Looped	Teflon
21	Wool	Looped	Leather
22	Acrylic	Looped	Leather
23	Acrylic	Looped	Rubber
24	Acrylic	Looped	Teflon
25	Polyester	Looped	Teflon
26	Polyester	Looped	Rubber
27	Polyester	Looped	Leather
28	Nylon 6	Looped	Teflon
29	Nylon 6	Looped	Rubber
30	Nylon 6	Looped	Leather
31	Nylon 6,6	Looped	Teflon
32	Nylon 6,6	Looped	Rubber
33	Nylon 6,6	Looped	Leather

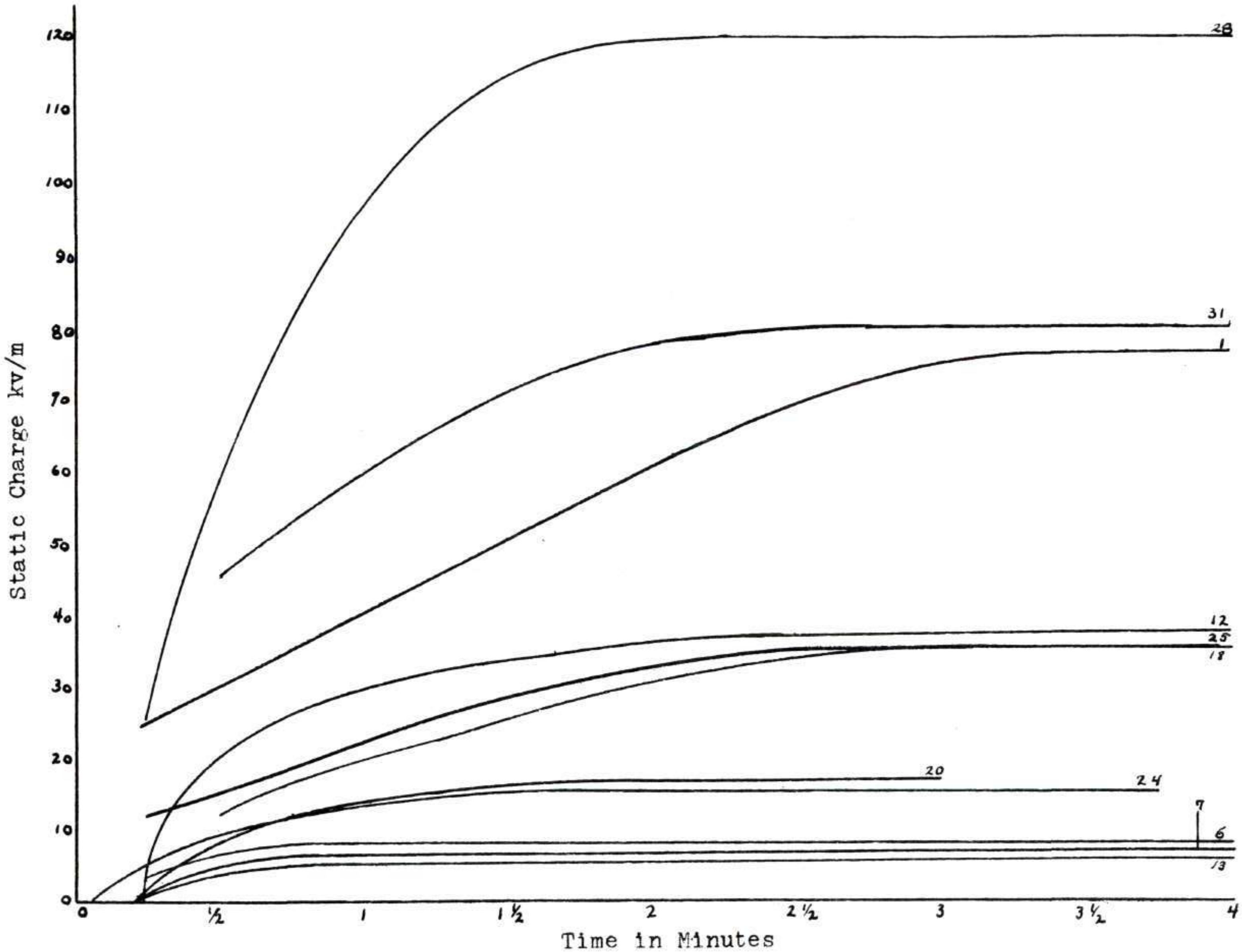


Figure 15. Static Build Up Produced With a Teflon Generator at 3 RPM

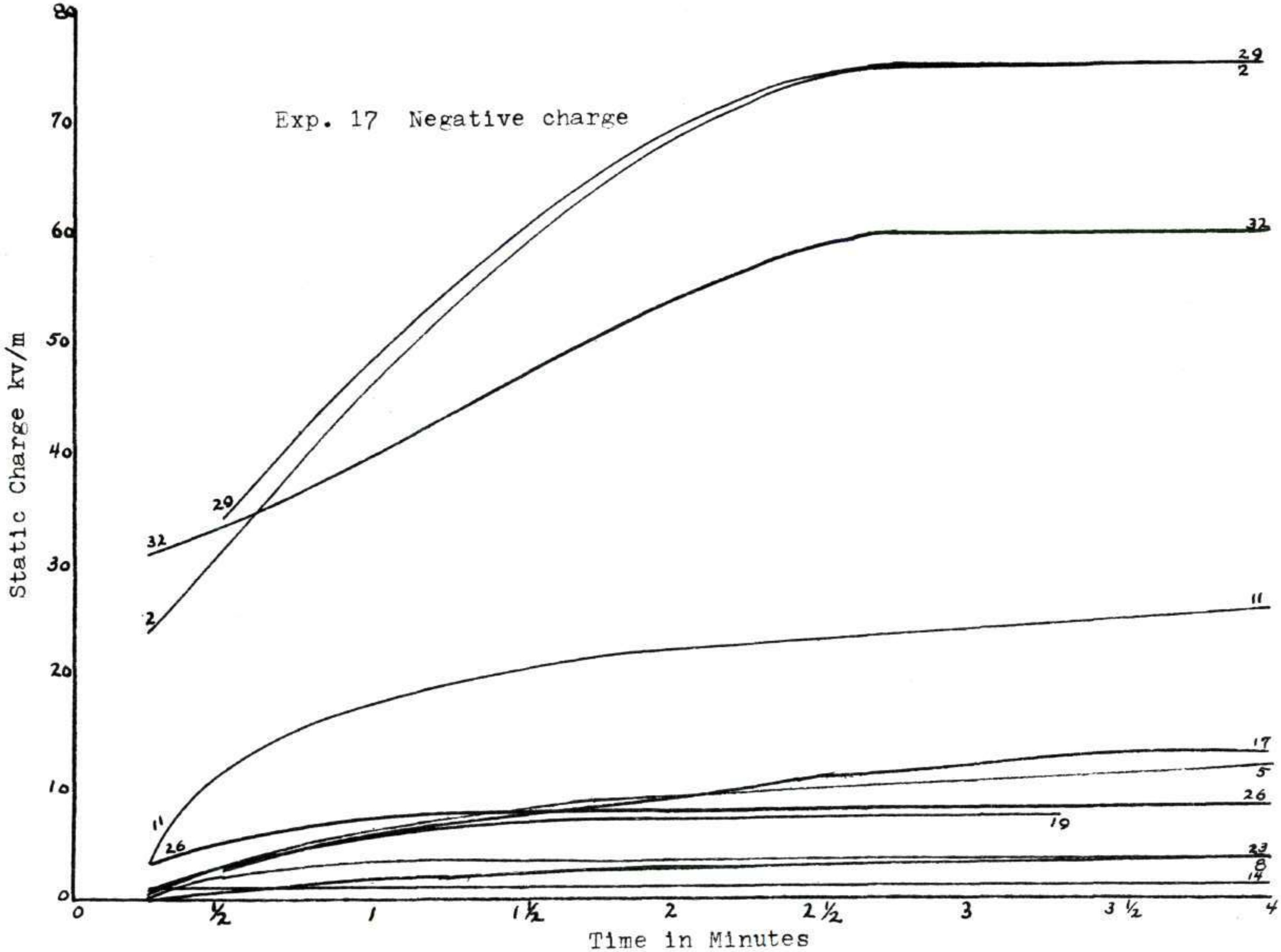


Figure 16. Static Build Up Produced With a Rubber Generator at 3 RPM

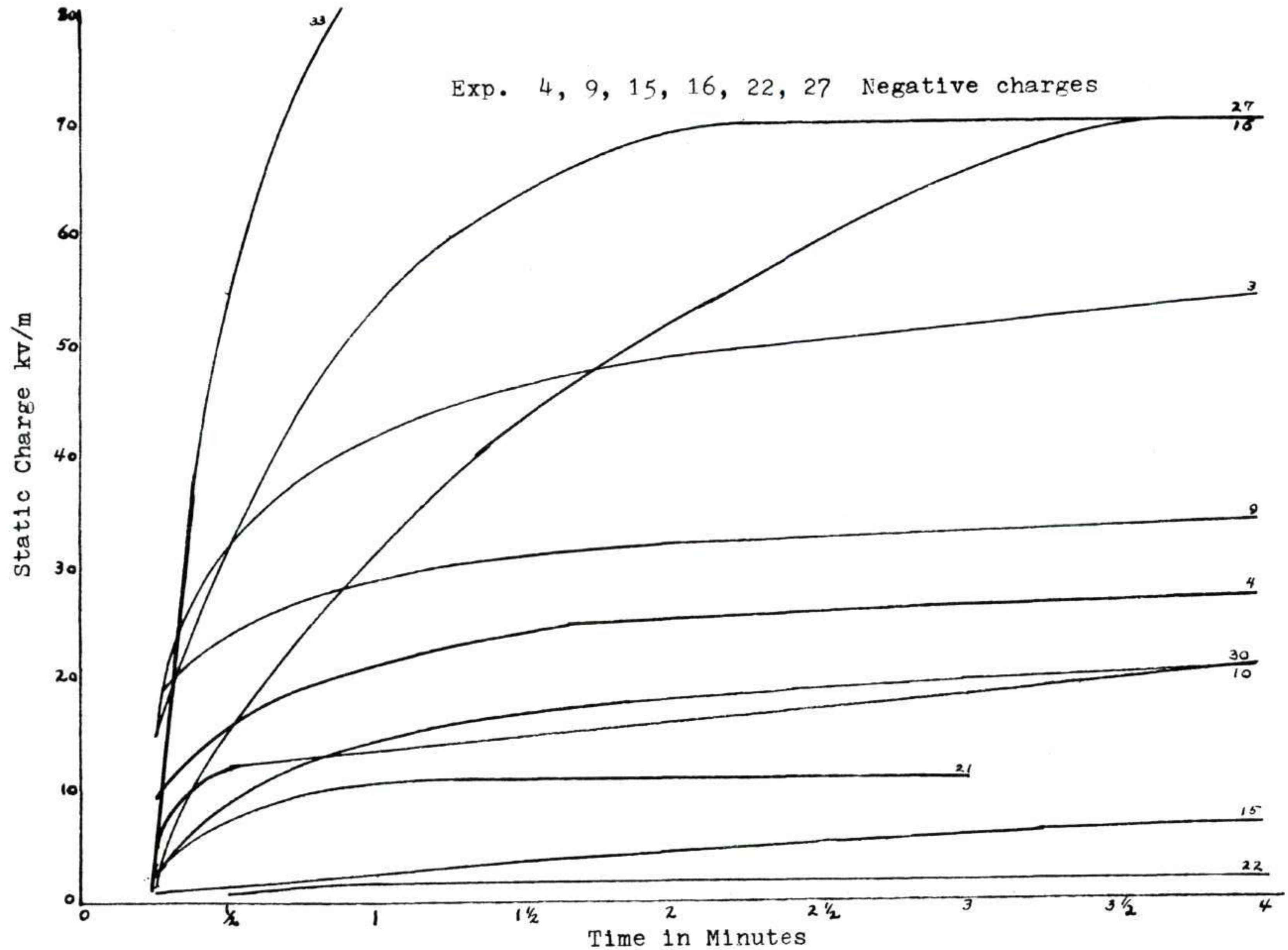


Figure 17. Static Build Up Produced With a Leather Generator at 3 RPM

the greatest static charge, two are polyester and one is nylon. Of the three, nylon carpet tested with Teflon set up the largest charge of static.

Geometry of the yarn in a carpet also plays an important role in static build up. Looped carpet yarn gives a rough hand to a carpet while a cut pile gives a soft smooth hand. A rough looped pile carpet will produce more friction with a static generator sliding across it than a smoother cut looped pile will produce. Since friction supplies energy to the system, electrons are able to jump from their original band to the conductance band, thus increasing the ability of the carpet to set up static charge. This is proved in the experiments. Sixty per cent of the cut looped pile samples set up less than 40 kv/m of static, 88 per cent set up static charges below 40 kv/m, and only one sample produced a static charge above 40 kv/m. Here one can see that cut looped pile carpets set up less static than looped pile carpets.

Table 3. Comparison of Static Build Up on Cut Looped Pile and Looped Pile

Static Build Up	Cut Pile	Looped Pile
Less than 30 kv/m	60%	71%
Less than 40 kv/m	89%	71%
Greater than 40 kv/m	11%	29%

From Table 3 it is seen that looped pile carpets have either low static charge, less than 30 kv/m, or high static charge, greater than 40 kv/m. Cut looped pile carpets have their static charge spread out over a larger range.

Dielectric Constant

Dielectric constants are very important in predicting static. It is known that if two materials are in contact, the material with the greater dielectric constant will become positively charged since it more readily loses electrons. Teflon, since it has a low dielectric constant of two, became negatively charged on every occasion because all of the fibrous materials studied had higher dielectric constants. Rubber became positively charged only once and that was with a polyester carpet. However, with a sample of polyester from a different manufacturer, rubber was negatively charged. This shows that there is a difference in the polymetric constituents of each polyester material. One polyester carpet has a greater dielectric constant than the other and the dielectric constant of rubber lies between the dielectric constants of these two polyester carpet samples. See Table 4.

Leather has the highest dielectric constant of the static-generating materials. It is able to give electrons to polyester and acrylic carpets, but receives electrons from nylon and wool.

Those materials with the greatest difference in dielectric constants will generate the greatest quantity of static charge. Table 4 indicates that Teflon on nylon should produce the greatest quantity of static, and from Figure 16 we see that it does. Wool does not follow this rule because its moisture regain is so great compared to synthetic fibers. The static charge on acrylic carpets will be small since its dielectric constant is close to the dielectric constants of the three static generators.

Table 4. Dielectric Constants[30]

Fiber	@ 65% Relative Humidity
Wool	5.5
Nylon	4.0
Leather	3.0
Acrylic	2.8
Rubber	2.4
Polyester	2.3 - 2.5
Teflon	2.0

The speed at which the static is generated is one determining factor to the amount of static set up on a carpet. To simulate different speeds of walking or running, the wheel on which the carpet is mounted is operated at 3, 5, and 10 revolutions per minute. The static charge increased with the increasing speed on all carpets unless an equilibrium was reached first. Equilibrium was not reached in many cases, indicating that a higher static charge was still obtainable. The small change from 3 to 5 revolutions per minute increased the static considerably; as much as 20 kv/m with some samples, as shown on Table 5. However, the increase from 5 to 10 revolutions per minute shows an even greater increase of static; as much as 60 kv/m. There is no proportional or mathematical increase that one could detect. Static charge increase is dependent on the fiber and the static generating material.

From Table 5 one can see that rubber shows the least static charge increase due to the increase of revolutions per minute from 3 to 10, while leather showed the largest increase. Also this table points out that nylon shows the greatest static charge increase of the fibers with increased revolutions per minute while the acrylics show the least increase. The fact that greater energy is introduced to the system at higher speeds is the obvious answer to the increase in static. As another observation though, the carpet samples with the highest static charge vary more than those with less static charge. For example, with leather on nylon, the highest static charge, the variation is some 100 kv/m. With leather on acrylic, the lowest static charge, the variation is about 12 kv/m. The static charge will vary more on materials which set up large quantities of static, than it will on those materials which set up less static.

The rate of build up can be given a numerical value by plotting the log of static charge versus the log of time. This plot is a straight line during the build up. Due to the distance between the sensing head and the static generating material, there is a small time lapse in setting up the static and recording it. This causes the plotted line to be slightly curved during the first few seconds. So actually the plotted straight line is the build up process.

Table 5. Maximum Static Charge Set Up on Carpet Samples in kv/m

Carpet Fiber and Type of Pile	Rubber			Leather			Teflon		
	3 RPM	5 RPM	10 RPM	3 RPM	5 RPM	10 RPM	3 RPM	5 RPM	10 RPM
Nylon 6 - Looped	75	85	90	65	90	170	72.5	90	140
Nylon 6,6 - Looped	65	72	79	125	190	270	80	87	90
Nylon 6,6 - Cut	35	57	65	25	47	70	37	51	60
Acrylic - Looped	3.3	4.5	7.5	-36	-58	-88	6.2	8	12.5
Acrylic - Cut	1.6	2.6	3.9	-7.5	-13.5	-19.5	4.5	6	7.5
Polyester - Looped (Exp. carpet)	8.1	8.1	9	-65	-100	-120	35	37	42
Polyester - Cut	-13	-13	-13	-70	-90	-115	35	50	60
Wool - Looped	6.5	7.5	8	11	14	18	16.5	23	32
Polypropylene - Looped	12	17	18.5	-27	-40	-59	7.5	11	15

Table 6. Rate of Build Up of Carpet Samples

Experiment Number	Carpet Fiber	Carpet Type	Static Generator	Rate of Build Up ln(kv/m sec)
1	Nylon 6	Looped	Teflon	.50
2	Nylon 6	Looped	Rubber	.70
3	Nylon 6	Looped	Leather	.77
4	Polypropylene	Looped	Leather	.55
5	Polypropylene	Looped	Rubber	.36
6	Polypropylene	Looped	Teflon	.21
7	Acrylic	Looped	Teflon	.52
8	Acrylic	Looped	Rubber	.40
9	Acrylic	Looped	Leather	.31
10	Nylon 6,6	Cut	Leather	.26
11	Nylon 6,6	Cut	Rubber	.35
12	Nylon 6,6	Cut	Teflon	.39
13	Acrylic	Cut	Teflon	.40
14	Acrylic	Cut	Rubber	.22
15	Acrylic	Cut	Leather	.78
16	Polyester	Cut	Leather	.70
17	Polyester	Cut	Rubber	1.29
18	Polyester	Cut	Teflon	.69
19	Wool	Looped	Rubber	.42
20	Wool	Looped	Teflon	.58
21	Wool	Looped	Leather	.43
22	Acrylic	Looped	Leather	.73
23	Acrylic	Looped	Rubber	.39
24	Acrylic	Looped	Teflon	.38
25	Polyester	Looped	Teflon	.57
26	Polyester	Looped	Rubber	.14
27	Polyester	Looped	Leather	.25
28	Nylon 6	Looped	Teflon	.26
29	Nylon 6	Looped	Rubber	.51
30	Nylon 6	Looped	Leather	.65
31	Nylon 6,6	Looped	Teflon	.40
32	Nylon 6,6	Looped	Rubber	.44
33	Nylon 6,6	Looped	Leather	.38

From these values one can determine the slope of the line. This slope is a numerical value which is the rate of build up and can be determined from a normal X,Y plot using the formula

$$\frac{X_2 - Y_1}{X_2 - X_1} \tag{4}$$

Polyester, Exp. 17 on Table 6, has the lowest rate of build up. This seeming contradiction can be explained by the fact that two different samples are involved and that each sample has an opposite charge. The fibers are also produced by two different manufacturers. Nylon and polyester with all three static generating materials and acrylic with leather also have relatively high build up rates. Table 6 shows such rates of build up.

These results are valuable, but they show only the rate at which the maximum was reached and not the maximum static charge. These rates of build up cannot be correlated to Figures 15, 16, and 17 because of the scale on which they were plotted.

Carpets made of wool, acrylic, polypropylene, and in some instances polyester, regardless of their rates of build up, do not set up large quantities of static. On carpets which generate a large quantity of static, the rate of build up is important since it is proportional to the speed at which this charge is acquired. Of the samples producing the greatest charge only one, polyester, Exp. 27 on Table 6, has a rate of build up less than .50 ln (kv/m sec). A person would have to walk on this carpet sample a longer period of time to build up the maximum static charge.

Static Decay

Unlike static build up, static decay should be the same for each sample. The static generating material is not a variable in decay. The static built up on a sample by each of the static generating materials should decay at the same rate regardless of the generator used.

Like static build up, static decay will also give a straight line when the log of time is plotted against the log of static charge. The rate of decay can be obtained by evaluating the slope of the line.

After the static charge was built up on each of the carpet samples at three revolutions per minute and at ten revolutions per minute, it was allowed to decay. Tables 7 and 8 show these rates of decay. Although the rates of decay of the polyester, the polypropylene, and one sample of nylon 6 remained approximately the same, most of the rates of decay increased at ten revolutions per minute. The cause of the rate of increase in decay at ten revolutions per minute is unknown. Wool, the only natural fiber tested, has the same or perhaps a little slower rate of decay at ten revolutions per minute.

Even though each polyester fiber was produced by a different manufacturer their rates of decay were very similar. Both are relatively slow to decay, and show little change between three and ten revolutions per minute. This shows that the basic copolymers of terephthalic acid and ethylene glycol still exert some controlling factor on static decay.

The acrylic samples were very similar in their rates of decay.

Table 7. Rate of Static Decay on Carpet at 3 RPM

Experiment Number	Carpet Fiber	Carpet Type	Static Generator	Rate of Decay at 3 RPM ln(kv/m min)
1	Nylon 6	Looped	Teflon	-.46
2	Nylon 6	Looped	Rubber	-.46
3	Nylon 6	Looped	Leather	-.43
4	Polypropylene	Looped	Leather	-.22
5	Polypropylene	Looped	Rubber	-.18
6	Polypropylene	Looped	Teflon	-.22
7	Acrylic	Looped	Teflon	-.73
8	Acrylic	Looped	Rubber	-.87
9	Acrylic	Looped	Leather	-.63
10	Nylon 6,6	Cut	Leather	-.71
11	Nylon 6,6	Cut	Rubber	-.67
12	Nylon 6,6	Cut	Teflon	-.73
13	Acrylic	Cut	Teflon	-.68
14	Acrylic	Cut	Rubber	-.62
15	Acrylic	Cut	Leather	-.80
16	Polyester	Cut	Leather	-.24
17	Polyester	Cut	Rubber	-.23
18	Polyester	Cut	Teflon	-.25
19	Wool	Looped	Rubber	-.71
20	Wool	Looped	Teflon	-.67
21	Wool	Looped	Leather	-.75
22	Acrylic	Looped	Leather	-.85
23	Acrylic	Looped	Rubber	-.82
24	Acrylic	Looped	Teflon	-.81
25	Polyester	Looped	Teflon	-.28
26	Polyester	Looped	Rubber	-.31
27	Polyester	Looped	Leather	-.31
28	Nylon 6	Looped	Teflon	-.18
29	Nylon 6	Looped	Rubber	-.21
30	Nylon 6	Looped	Leather	-.27
31	Nylon 6,6	Looped	Teflon	-.34
32	Nylon 6,6	Looped	Rubber	-.34
33	Nylon 6,6	Looped	Leather	-.36

Table 8. Rate of Static Decay on Carpet at 10 RPM

Experiment Number	Carpet Fiber	Carpet Type	Static Generator	Rate of Decay at 10 RPM ln(kv/m min)
1	Nylon 6	Looped	Teflon	-.60
2	Nylon 6	Looped	Rubber	-.60
3	Nylon 6	Looped	Leather	-.60
4	Polypropylene	Looped	Leather	-.37
5	Polypropylene	Looped	Rubber	-.17
6	Polypropylene	Looped	Teflon	-.35
7	Acrylic	Looped	Teflon	-.85
8	Acrylic	Looped	Rubber	-.86
9	Acrylic	Looped	Leather	-.79
10	Nylon 6,6	Cut	Leather	-.92
11	Nylon 6,6	Cut	Rubber	-.94
12	Nylon 6,6	Cut	Teflon	-.92
13	Acrylic	Cut	Teflon	-.85
14	Acrylic	Cut	Rubber	-.84
15	Acrylic	Cut	Leather	-.85
16	Polyester	Cut	Leather	-.26
17	Polyester	Cut	Rubber	-.15
18	Polyester	Cut	Teflon	-.29
19	Wool	Looped	Rubber	-.62
20	Wool	Looped	Teflon	-.63
21	Wool	Looped	Leather	-.63
22	Acrylic	Looped	Leather	-.90
23	Acrylic	Looped	Rubber	-.88
24	Acrylic	Looped	Teflon	-.90
25	Polyester	Looped	Teflon	-.35
26	Polyester	Looped	Rubber	-.37
27	Polyester	Looped	Leather	-.30
28	Nylon 6	Looped	Teflon	-.23
29	Nylon 6	Looped	Rubber	-.23
30	Nylon 6	Looped	Leather	-.30
31	Nylon 6,6	Looped	Teflon	-.66
32	Nylon 6,6	Looped	Rubber	-.46
33	Nylon 6,6	Looped	Leather	-.71

All three samples decayed quickly and at approximately the same rate. Each sample's rate of decay was increased considerably when the revolutions per minute were increased.

Wool had a high rate of decay as expected. The decay at ten revolutions per minute was, however, slightly less than at the slower three revolutions per minute. All the other samples had higher rates of decay at ten revolutions per minute. As has been pointed out, it was the only natural fiber used in this experiment. Perhaps the increase was due to the production process or the shape of the synthetic fibers. The wool fibers have scales on their exterior while the synthetic fibers do not.

Polypropylene, the most recently developed fiber among the samples, had a relatively low rate of decay. This was to be expected since its moisture content is essentially zero. Thus it must rely on the moisture of the atmospheric surroundings to dissipate the electronic charge. Other synthetic fibers with a varying range of moisture content may rely on the atmosphere to dissipate the static charge.

Nylon 6, and nylon 6,6 had a decay range from medium to low except for the cut looped pile sample. This was because the fine fibers were better conductors than the more bulky looped fibers. Since the cut sample was a better conductor than the looped, it should have had and did have, a higher rate of decay. This should have happened in all the cases of cut looped pile carpet versus looped pile carpet, but since the charge must be large in most cases, it didn't have the same effect as on nylon.

All the nylon samples showed an increase in the rate of decay when the speed of the build up was increased. Nylon had the highest decay rate of all the samples tested.

Since the plot of the log of static and the log of time yields a straight line, the static charge may be predicted by using the formula for a straight line.

$$Y = mX + n \tag{5}$$

where Y = ln of static charge

m = slope of line (rate)

X = ln of time

n = constant

This equation does not allow for the effect of the humidity, the temperature, the velocity at which the static charge is set up, or the construction of the carpet. The new equation will be

$$abcY = mX + n + k \tag{6}$$

where a, b, c, n, k = constants

(k = constant of carpet construction)

Y = ln of static charge

X = ln of time

m = slope of line (rate)

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The polyester cut looped pile carpet sample tested with rubber as the static generating material, proved to have the highest rate of build up at three revolutions per minute. The looped pile carpet sample of polypropylene tested with Teflon as the static-generating material, and the cut looped pile carpet sample of acrylic tested with rubber as the static generating material had the lowest rates of build up at three revolutions per minute. The polyester looped pile carpet sample tested with rubber as the static-generating material was not considered as having a lower rate since it was an experimental carpet.

The acrylic looped pile carpet sample had the fastest rate of decay at three revolutions per minute. The looped pile carpet sample of polypropylene had the slowest rate of decay at three revolutions per minute.

The nylon 6,6 cut looped pile carpet sample had the fastest rate of decay at ten revolutions per minute. The cut looped pile carpet sample of polyester had the slowest rate of decay at ten revolutions per minute.

The nylon 6,6 looped pile carpet sample set up the greatest maximum static charge at three revolutions per minute when using leather as the static-generating material. The acrylic looped pile and the acrylic cut looped pile carpet samples set up the least maximum static charge when using leather and rubber, respectively, as the static-generating materials at three revolutions per minute, but with opposite charges.

The nylon 6,6 looped pile carpet sample, when tested with leather as the static-generating material, set up the greatest maximum static charge at ten revolutions per minute. The cut looped pile carpet sample of acrylic fiber, when tested with rubber as the static-generating material, set up the least maximum static charge at ten revolutions per minute.

When tested with each of the three generating materials, the nylon 6,6 cut looped pile carpet had lower rates of build up, higher rates of decay at three and at ten revolutions per minute, and lower maximum charges at ten and at three revolutions per minute than the nylon 6,6 looped pile sample.

The static-generating material is a controlling factor of the rate of build up and the maximum static charge, but it is not a controlling factor of the rate of decay. The maximum static charge set up at ten revolutions per minute is always equal to or greater than the maximum static charge at three revolutions per minute. The maximum static charge was reached in a matter of seconds or minutes while it required from 20 minutes to hours for the charge to decay.

Recommendations

There was a difference noted between the looped pile and the cut looped pile carpets in the rates of build up, in the rates of decay, and in the maximum static charge. Future experimenters could investigate the geometric structure of carpets, regarding its effect on the build up of static charge, the decay of static charge, and the maximum static charge.

One means of reducing static charge on carpets is the use of chemical agents called antistats. Work could be undertaken to evaluate the effectiveness of antistats and the duration of these antistats.

With each increase in velocity at which the static charge was set up in this investigation, the quantity of static charge on the carpet samples was increased. Research on this fact could be carried farther to determine if the static charge increases indefinitely or comes to equilibrium at some definite maximum. There were variations in the rates of decay of these charges set up by the elevated velocities. Inquiries could be made in this field to determine the causes of the variations in decay.

APPENDIX

Table 9. Summary of Experimental Data of Static Electricity on Carpet

Experiment Number	Carpet Fiber	Carpet Type	Static Generator	Rate of Build Up ln(kv/m sec)	Rate of Decay at 3 RPM ln(kv/m min)	Rate of Decay at 10 RPM ln(kv/m min)	Maximum Static Charge 3 RPM kv/m	Maximum Static Charge 10 RPM kv/m
1	Nylon 6	Looped	Teflon	.50	-.46	-.60	75	140
2	Nylon 6	Looped	Rubber	.70	-.46	-.60	77	90
3	Nylon 6	Looped	Leather	.77	-.43	-.60	65	170
4	Polypropylene	Looped	Leather	.55	-.22	-.37	-27	-59
5	Polypropylene	Looped	Rubber	.36	-.18	-.17	12	18.5
6	Polypropylene	Looped	Teflon	.21	-.22	-.35	7.5	15
7	Acrylic	Looped	Teflon	.52	-.73	-.85	6.2	12.5
8	Acrylic	Looped	Rubber	.40	-.87	-.86	3.25	7.5
9	Acrylic	Looped	Leather	.31	-.63	-.79	-36	-88
10	Nylon 6,6	Cut	Leather	.26	-.71	-.92	25	70
11	Nylon 6,6	Cut	Rubber	.35	-.67	-.94	35	65
12	Nylon 6,6	Cut	Teflon	.39	-.73	-.92	37	65
13	Acrylic	Cut	Teflon	.40	-.68	-.85	4.5	7.5
14	Acrylic	Cut	Rubber	.22	-.62	-.84	1.6	3.9
15	Acrylic	Cut	Leather	.78	-.80	-.85	-7.5	-19.5
16	Polyester	Cut	Leather	.70	-.24	-.26	-70	-115
17	Polyester	Cut	Rubber	1.29	-.23	-.15	-13	-13
18	Polyester	Cut	Teflon	.69	-.25	-.29	35	60
19	Wool	Looped	Rubber	.42	-.71	-.62	6.5	8
20	Wool	Looped	Teflon	.58	-.67	-.63	16.5	32
21	Wool	Looped	Leather	.43	-.75	-.63	11	18

Table 9. Summary of Experimental Data of Static Electricity on Carpet (Cont.)

Experiment Number	Carpet Fiber	Carpet Type	Static Generator	Rate of Build Up ln(kv/m sec)	Rate of Decay 3 RPM ln(kv/m min)	Rate of Decay 10 RPM ln(kv/m min)	Maximum Static Charge 3 RPM kv/m	Maximum Static Charge 10 RPM kv/m
Cont.								
22	Acrylic	Looped	Leather	.73	-.85	-.90	-1.6	-10
23	Acrylic	Looped	Rubber	.39	-.82	-.88	3.5	7
24	Acrylic	Looped	Teflon	.38	-.81	-.90	15	31
25	Polyester	Looped	Teflon	.57	-.28	-.35	35	42
26	Polyester	Looped	Rubber	.14	-.31	-.37	8.1	9.0
27	Polyester	Looped	Leather	.25	-.31	-.30	-65	-120
28	Nylon 6	Looped	Teflon	.26	-.18	-.23	120	120
29	Nylon 6	Looped	Rubber	.51	-.21	-.23	77.5	130
30	Nylon 6	Looped	Leather	.65	-.27	-.30	22	125
31	Nylon 6,6	Looped	Teflon	.40	-.34	-.66	80	95
32	Nylon 6,6	Looped	Rubber	.44	-.34	-.46	65	79
33	Nylon 6,6	Looped	Leather	.38	-.36	-.71	125	270

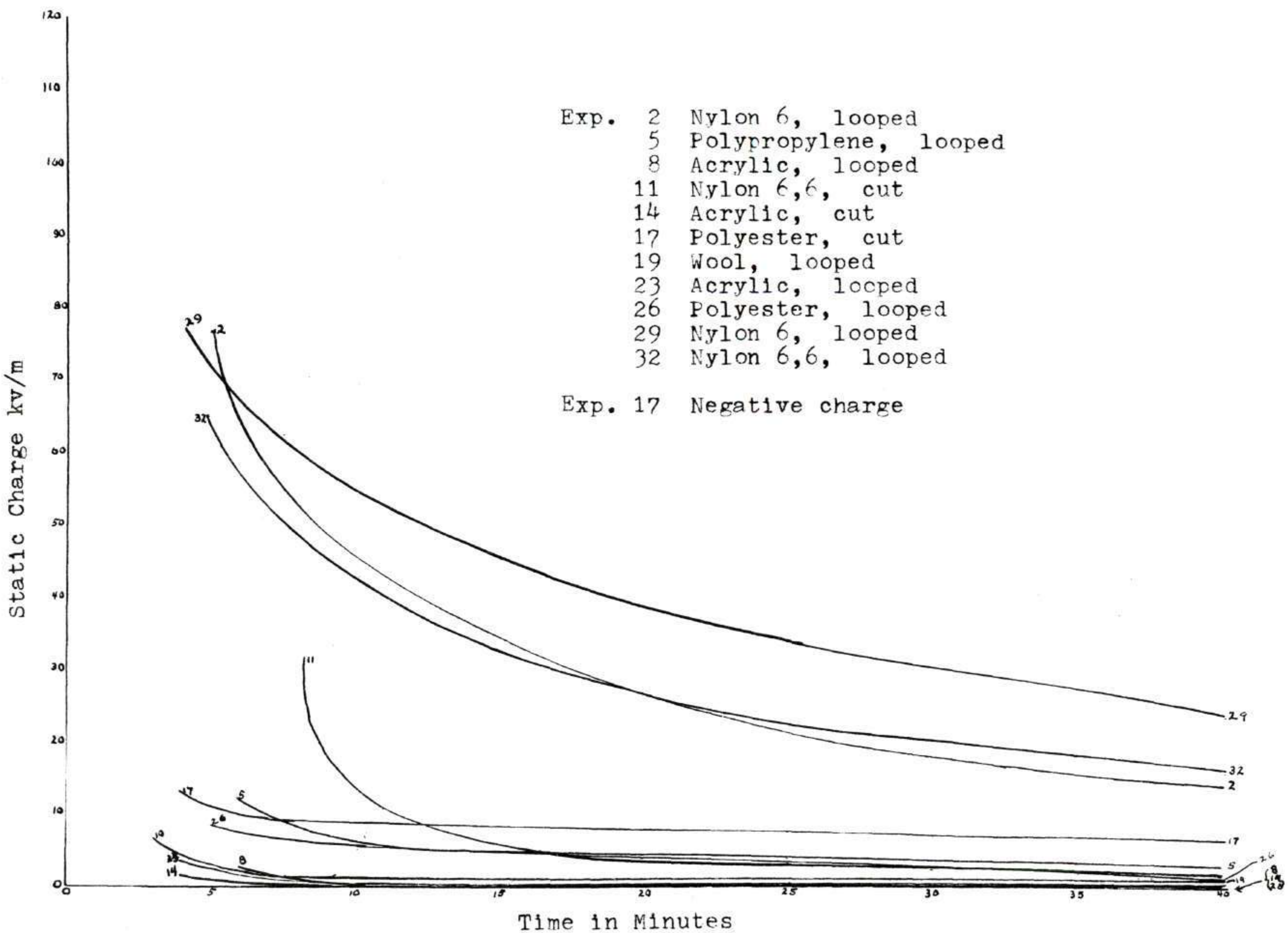


Figure 18. Decay of Static Produced With a Rubber Generator at 3 RPM

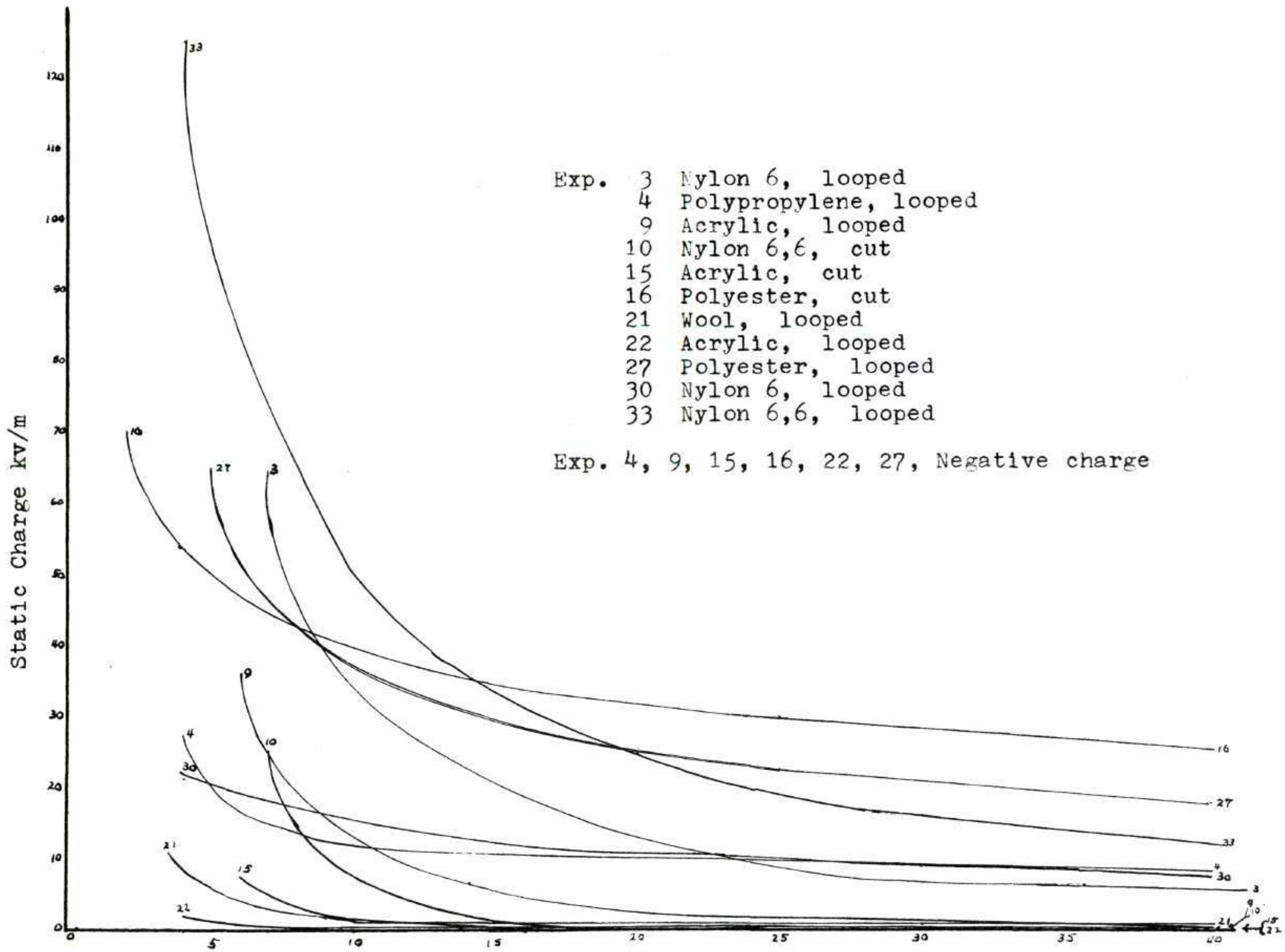


Figure 19. Decay of Static Produced With a Leather Generator at 3 RPM

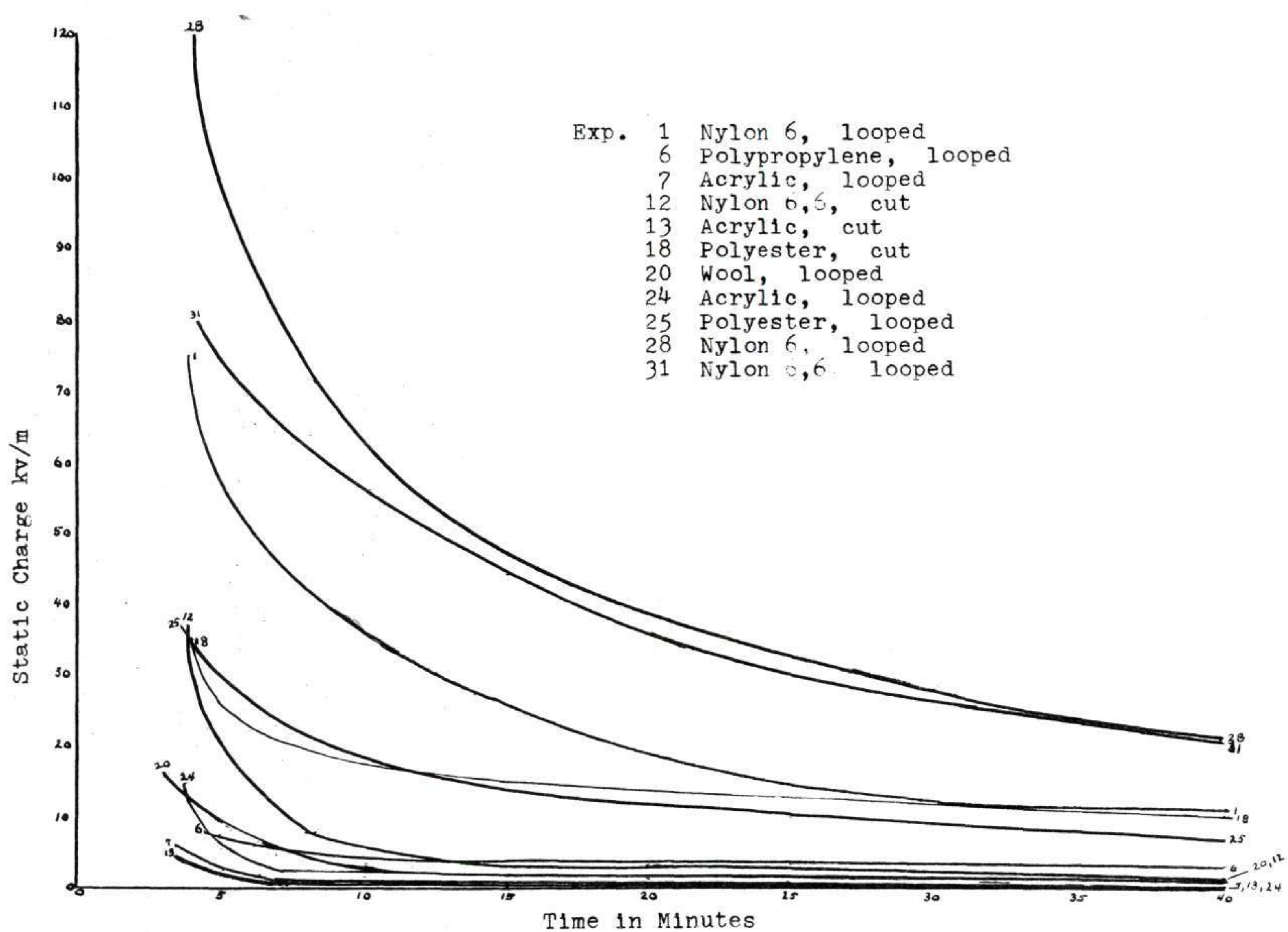


Figure 20. Decay of Static Produced With a Teflon Generator at 3 RPM

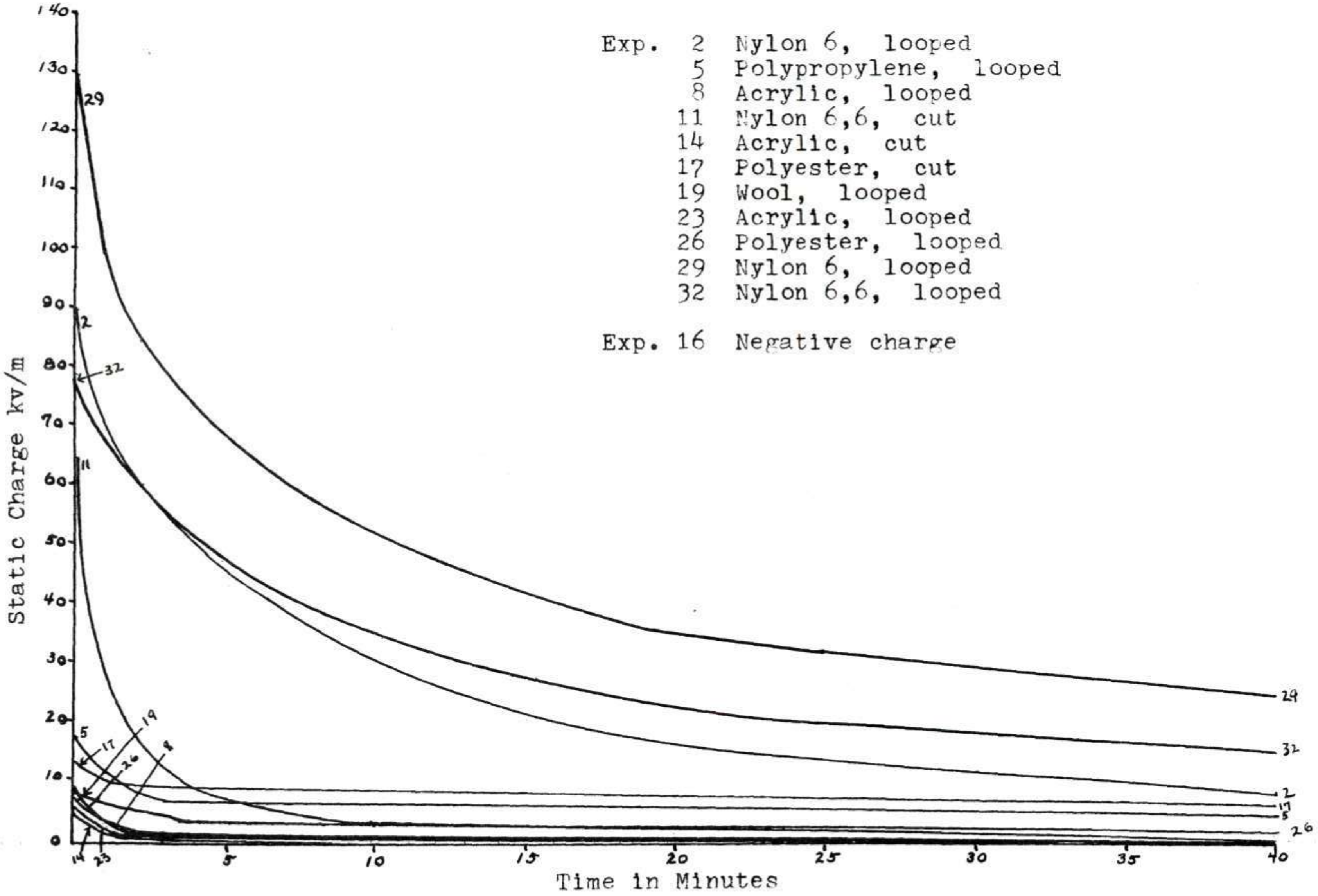


Figure 21. Decay of Static Produced With a Rubber Generator at 10 RPM

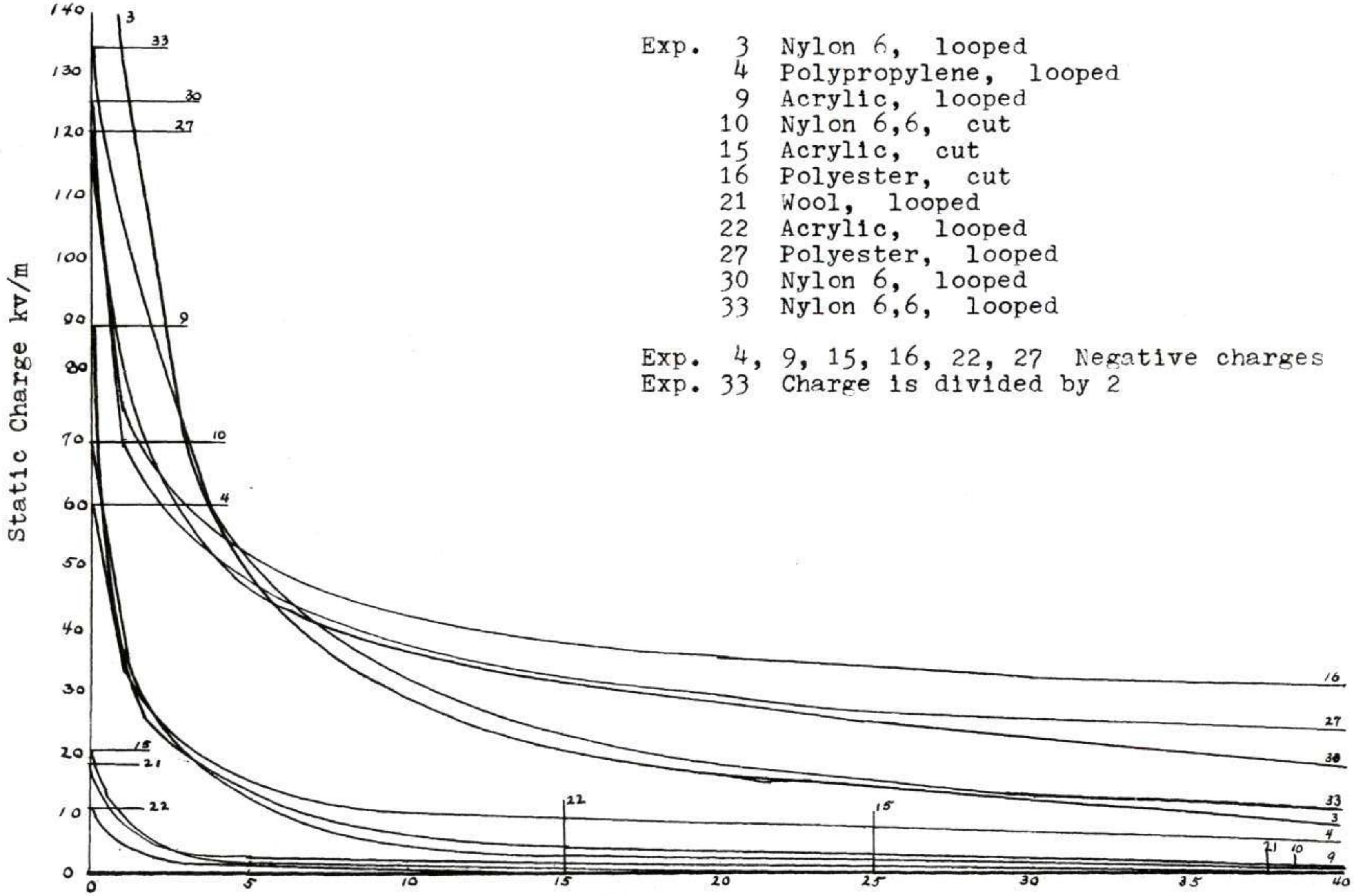


Figure 22. Decay of Static Produced With a Leather Generator at 10 RPM

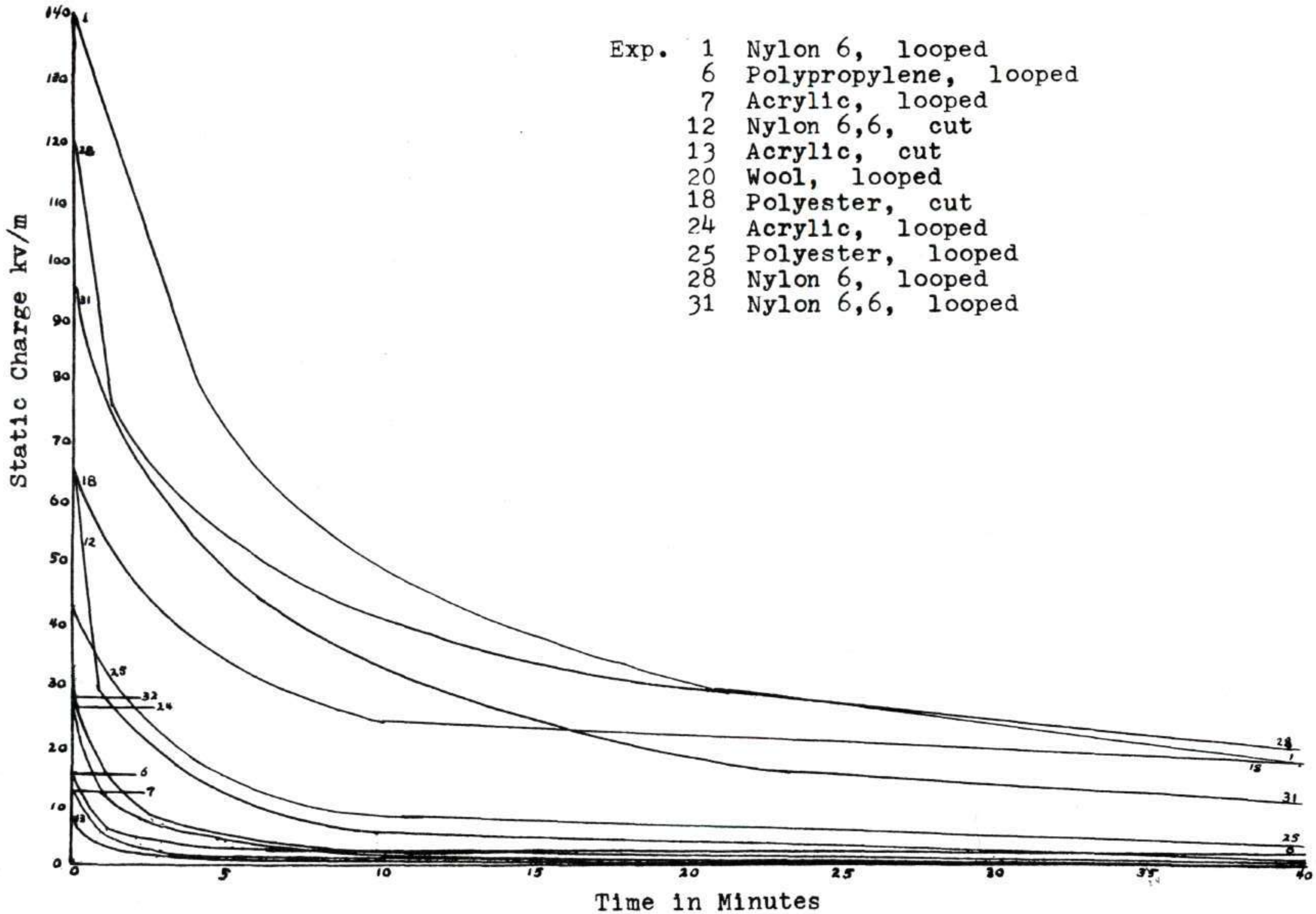


Figure 23. Decay of Static Produced With a Teflon Generator at 10 RPM

BIBLIOGRAPHY

1. S. M. Edelstein, "Amber First Material to Spark Interest in Static Electricity," *America's Textile Reporter 66* (47):69, 75 (Nov. 1952).

2. Joachim Gayler, Robert E. Wiggins, James B. Arthur, "Static Electricity, Generation, Measurement, and Its Effects on Textiles," *The Technology and Chemistry of Textiles, No. 5* (May, 1965), p. 1.

3. Joachim Gayler, Robert E. Wiggins, James B. Arthur, *Ibid.*

4. H. Helmholtz, *Ann. Phys. 7* (1879), p. 337.

5. P. E. Shaw, *Proc. Roy. Soc. A, 122,* (1929), p. 49.

6. H. Helmholtz, p. 337.

7. V. E. Gonsalves, "Some Fundamental Questions Concerning the Static Electrification of Textile Yarns: Part 1," *Textile Research Journal, 23* (10) (1953), p. 711-718.

8. D. F. Arthur, "A Review of Static Electrification," *Journal of the Textile Institute, 46* (12) (1955), p. T721-34.

9. Arthur Beiser, *Concepts of Modern Physics,* New York: McGraw-Hill Book Company Inc. (1963), p. 173.

10. D. F. Arthur, *op. cit.*

11. F. A. Vick, "Theory of Contact Electrification," *British Journal of Applied Physics, 4* (Suppl. No. 2) (1953), pp. S1-S5.

12. S. P. Hersh, D. J. Montgomery, "Static Electrification of Filaments: Theoretical Aspects," *Textile Research Journal, 26,* (1956), pp. 903-913.

13. W. R. Harper, *Proc. Roy. Soc.* (London), (1951) *A205,* p. 83.

14. F. A. Vick, *op. cit.*

15. D. J. Montgomery, *Solid State Physics, 9,* in *Advances in Research and Application,* F. Seitz and D. Turnbull, eds. New York: Academic Press, 1959, pp. 139-197.

16. D. J. Montgomery, *Ibid.*

17. Joachim Gayler, Robert E. Wiggins, and James B. Arthur, *op. cit.*, p. 10.

18. D. J. Lehmicke, "Static in Textile Processing," *American Dyestuff Reporter, 38* (24), (1949), pp. 853-855, 862.

19. S. P. Hersh and D. J. Montgomery, *op. cit.*

20. H. Frotscher, "The Antistatic Preparation of Synthetic Fibers," *Zeitschrift fur die gesamte Textilindustrie, 62* (18), (1960), pp. 746-750.

21. J. W. Ballou, "Static Electricity in Textiles," *Textile Research Journal, 24* (2), (1954), pp. 146-155.

22. Joachim Gayler, Robert E. Wiggins, and James B. Arthur, *op. cit.,* p. 10.

23. G. W. Graham, "Some Research on the Generation and Inhibition of Static Electricity," *Textile Mercury and Argus, 128* (3326), (1953), pp. 16, 19, 20, 23.

24. J. W. Ballou, *op. cit.*

25. Joachim Gayler, Robert E. Wiggins, and James B. Arthur, *op. cit.,* p. 36.

26. W. E. Morton and J. W. S. Hearle, *Physical Properties of Textile Fibers,* London, England, Butterworth & Co., (1962), pp. 487-523.

27. Joachim Gayler, Robert E. Wiggins and James B. Arthur, *op. cit.,* p. 28.

28. Joachim Gayler, Robert E. Wiggins and James B. Arthur, *op. cit.,* p. 27.

29. Joachim Gayler, Robert E. Wiggins and James B. Arthur, *op. cit.,* p. 27.

30. Joachim Gayler, Robert E. Wiggins and James B. Arthur, *op. cit.,* p. 12.